Search for Muonium to Antimuonium Conversion

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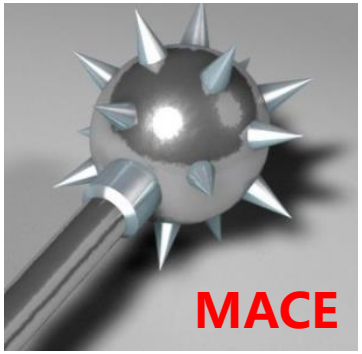
The RP frontier townhall meeting & cLFV (RF5) of Snowmass

In collaboration with

IHEP: Yukai Chen, Rui-Rui Fan, Zhilong Hou, Han-Tao Jin, Hai-Bo Li, Yang Li, Ying-Peng Song, Jing-Yu Tang, Nikolaos Vassilopoulos, Tian-Yu Xing, Ye Yuan, Yao Zhang, Guang Zhao, Luping Zhou …

SYSU: Yu Chen, Jing-Kun Chen, Yu-Zhe Mao, Zi-Xin Wang …

Osaka U: Chen Wu



Muonium to Antimuonium Conversion Experiment(MACE)

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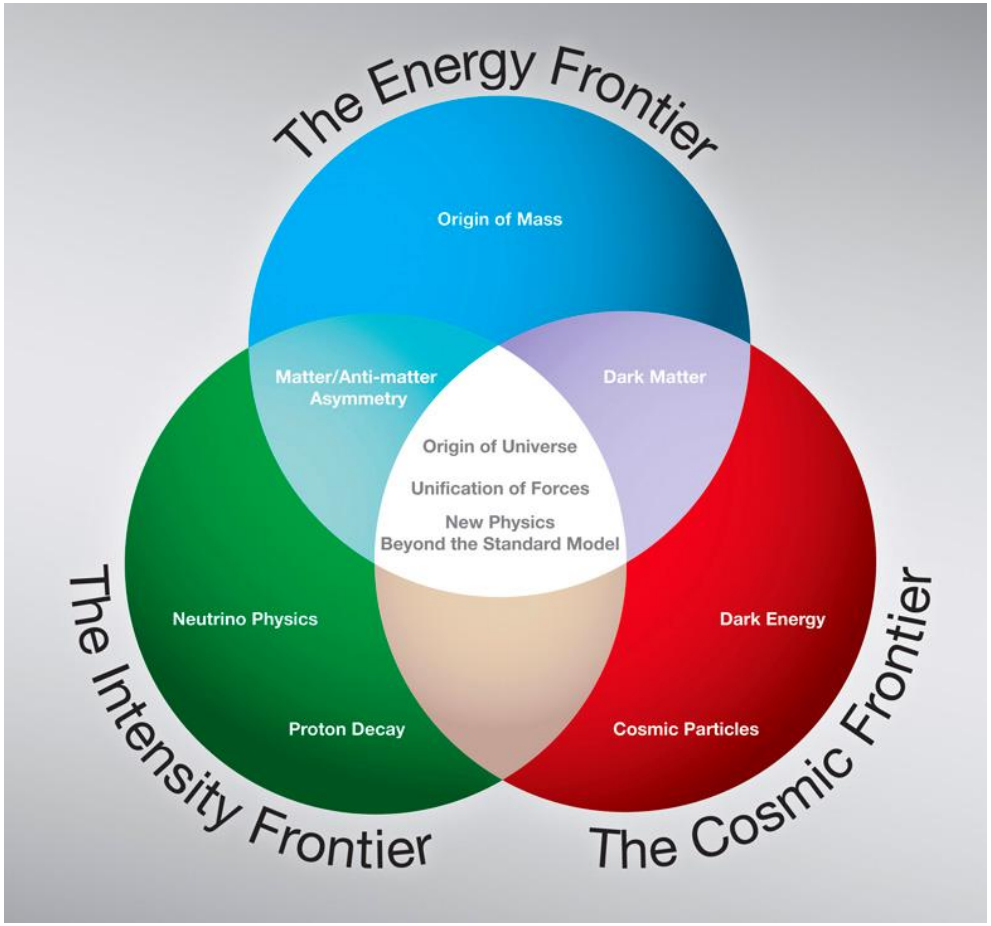
Three frontiers in Particle Physics



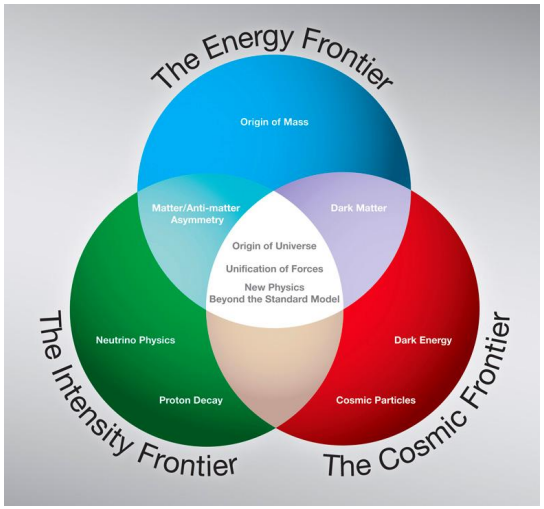
- High-energy frontier
- High-intensity frontier
- Cosmic Frontier

Search for new physics beyond SM:

- What's the origin of mass?
- Matter-antimatter asymmetry?
- What is DM?
- ……

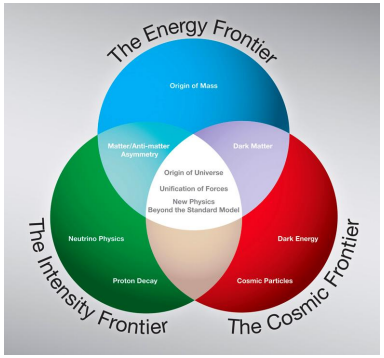
High-intensity/high-precision frontier

- Neutrino experiments
  - T2K, NOvA, T2HK, DUNE…
  - JUNO, MOMENT…
- cLFV:
  - Mu2e(FNAL) $\mu^- + Al \rightarrow e^- + Al$
  - COMET(J-PARC)
  - MEG-II(PSI) $\mu^+ \rightarrow e^+ + \gamma$
- LNV:
  - Mu3e(PSI) $\mu^+ \rightarrow e^+ e^- e^+$
- Precision measurements of μ:
  - MuLan&FAST at PSI: μ lifetime.
  - MuCap at PSI: couplings for μ captures.
  - MuSun to measure electroweak interactions and polarizations.
  - TWIST at TRIUMF to measure parameters in weak decays.
  - g-2 at FNAL to measure magnetic moment.
  - MeuSEUM at J-PARC to measure muonium hyper-fine structure.



High-intensity frontier

- Search for new physics with accelerator muons
  - Mu2e in US
  - COMET in Japan
  - MEG-II/Mu3e in Switzerland
  - **Muonium to Antimuonium Conversion Experiment in CSNS**

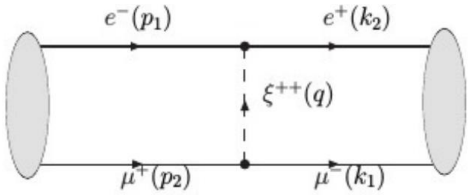


$$\mu^+ e^- \rightarrow \mu^- e^+$$

Naively proposed at the international Review of EMuS in November, 2018.

Muonium to antimuonium beyond SM.

- Lepton flavour violation process beyond SM.
- For example, predicted by type-II seesaw model.



$\mathcal{P}(M \to \bar{M})$	$G_{M\bar{M}}/G_F$	Experiment
$< 2.1 \times 10^{-6}$	< 0.29	Huber et al. (1990)
$< 6.5 \times 10^{-7}$	< 0.16	Matthias et al. (1991)
$< 8.0 \times 10^{-9}$	$< 1.8 \times 10^{-2}$	Abela et al. (1996)
$< 8.3 \times 10^{-11}$	$< 3 \times 10^{-3}$	Willmann et al. (1999)

The best limit!

Results 20 years ago!!!

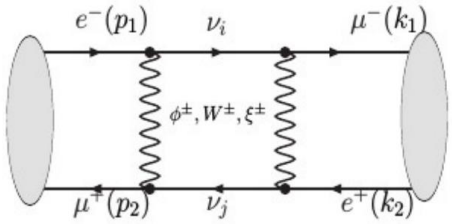


Figure 2.3: Dirac-Box (a)

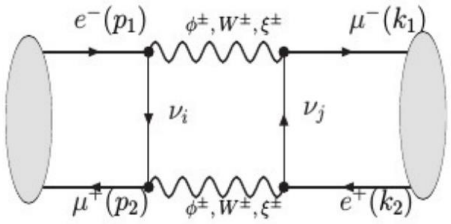


Figure 2.4: Dirac-Box (b)

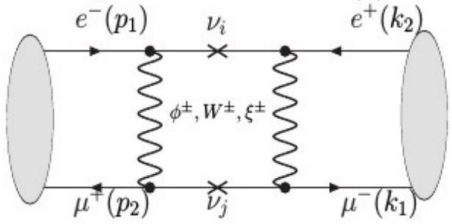


Figure 2.5: Majorana-Box (c)

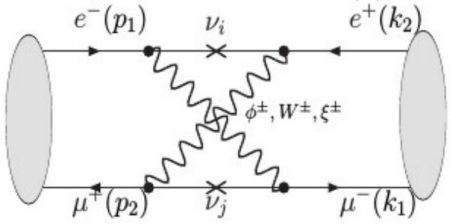


Figure 2.6: Majorana-Box (d)

- EFT study of muonium to antimuonium conversion by R. Conlin and A. Petrov, arXiv: 2005.10276

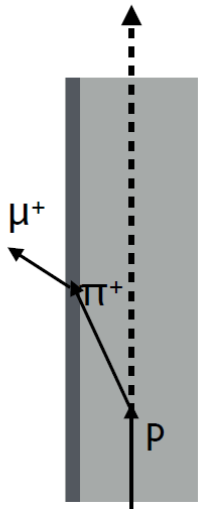
Muon and muonium productions

$$\text{relative } \mu^+ \text{yield} \propto \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

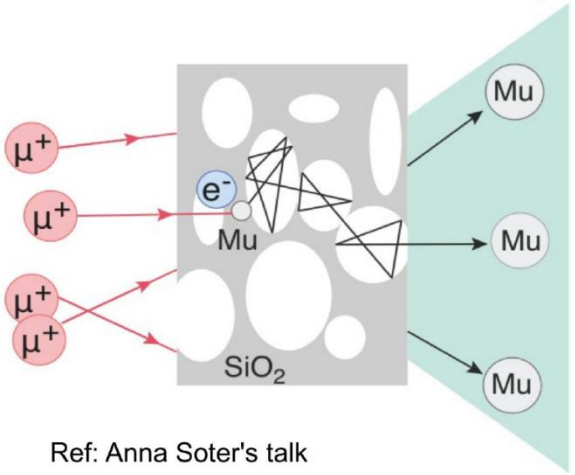
$$\propto \frac{1}{Z^{2/3}}$$



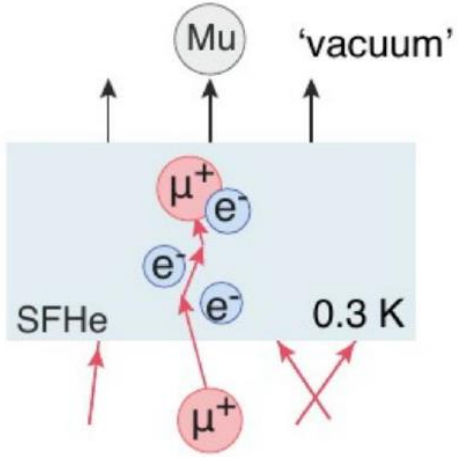
Previous experience

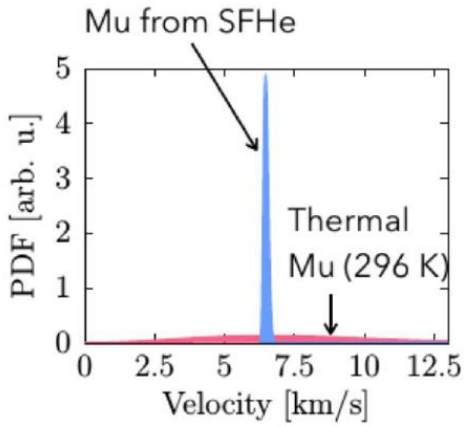
- Hot tungsten in 1986: 4% from 4 MeV μ^+
- SiO_2 powder in 1990: 1%-2% from 4 MeV μ^+
- SiO_2 film(cold) in 2012: 40% from 5 keV μ^+

Proposed target: aerogel, super fluid helium…



Ref: Anna Soter's talk





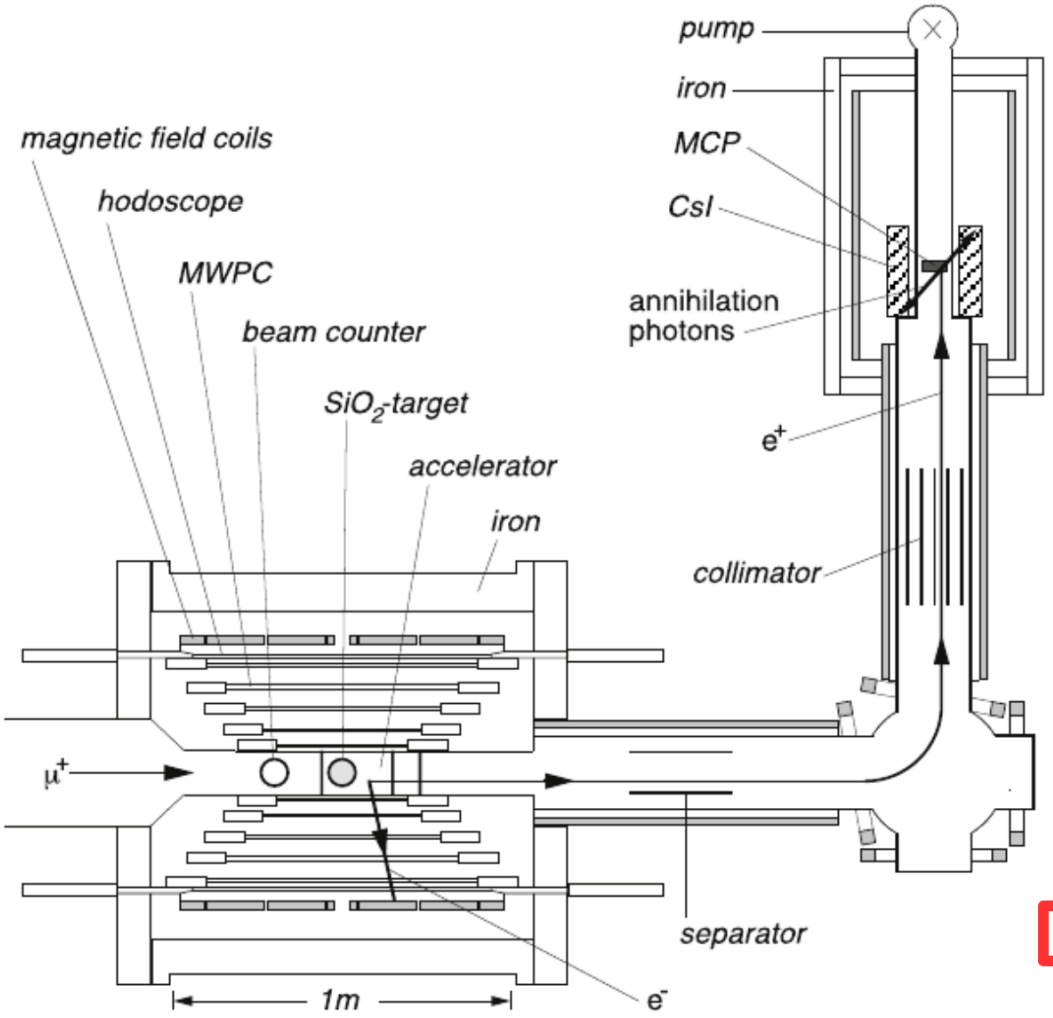
Silica powder

Increase efficiency

Super Fluid Helium

How to detect such a process in 1999?

- **Follow the apparatus at PSI built more than 20 years ago.**
- **Continous muon source: 8×10^6 μ^+/s, p=26 MeV with 5% spread.**



- Magnetic spectrometer to study the anti-muonium
- Signal one: energetic e^- from μ^- decay
- Signal two: atomic shell e^+, accelerated and guided onto a MCP
- Coincident signals: time and position.

$\mathcal{P}(M \to \bar{M})$	$G_{M\bar{M}}/G_F$	Experiment
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No progress since then!!!

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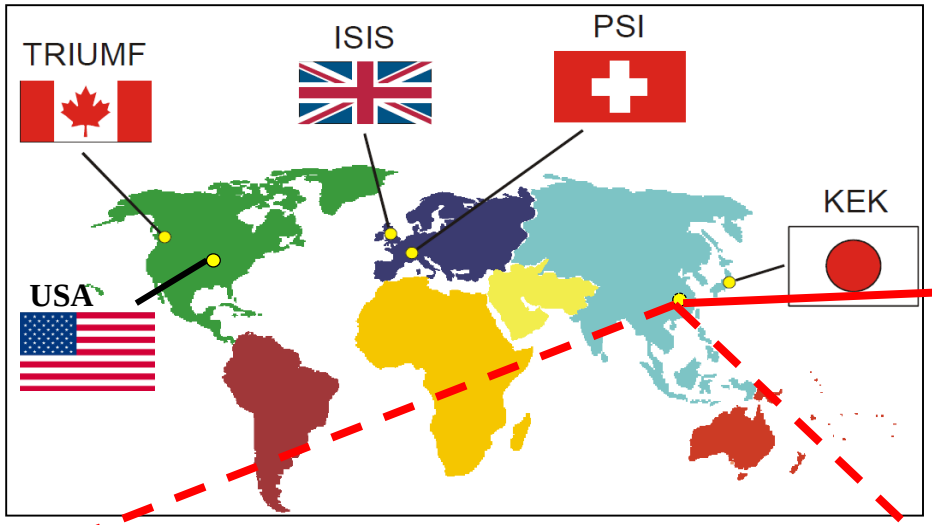
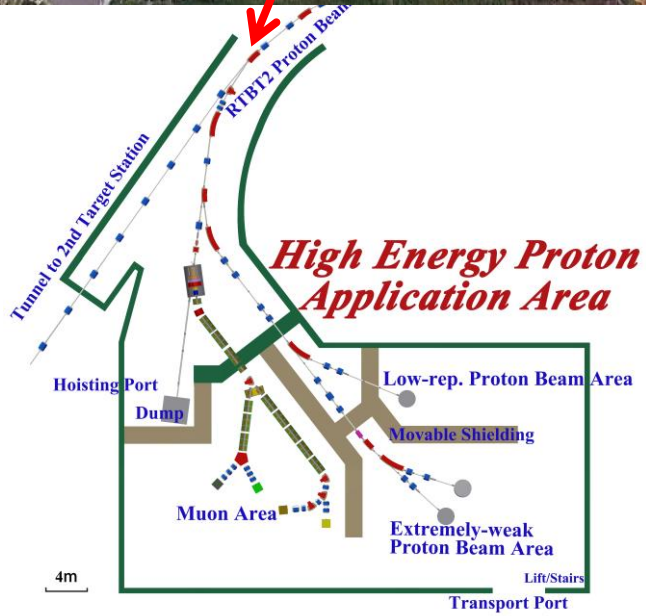
EMuS at China Spallation Neutron Source

- Build the first accelerator muon source for μSR in China?



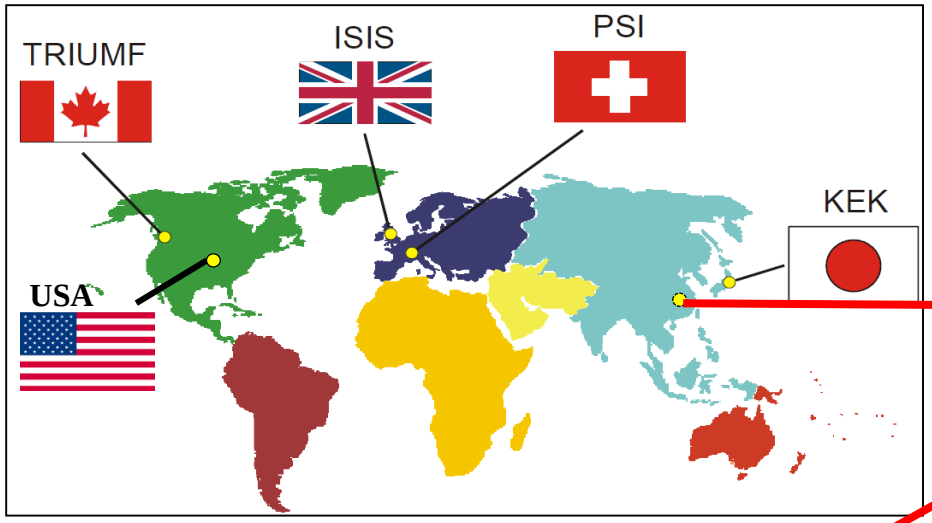
Guangdong-Hongkong-Macao in China
The Great Bay Area with several facilities

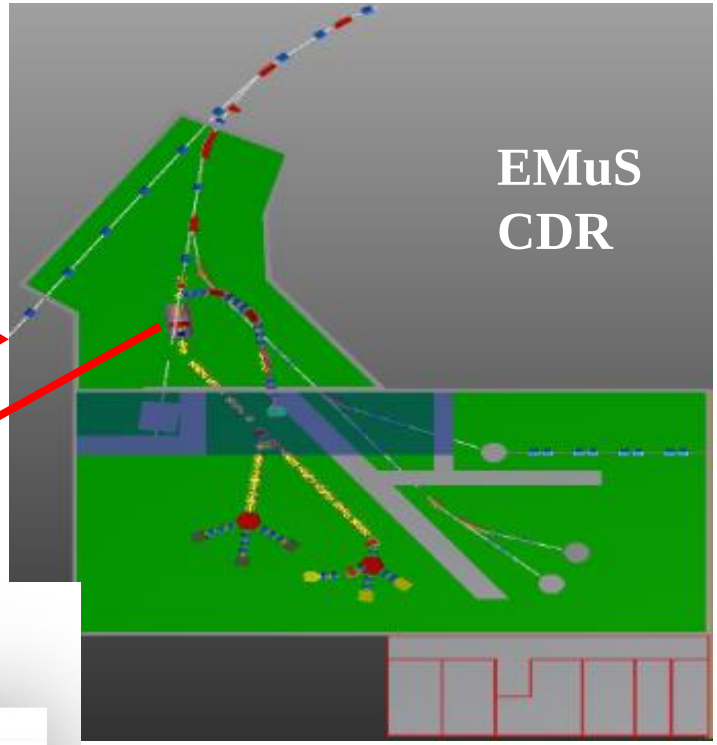


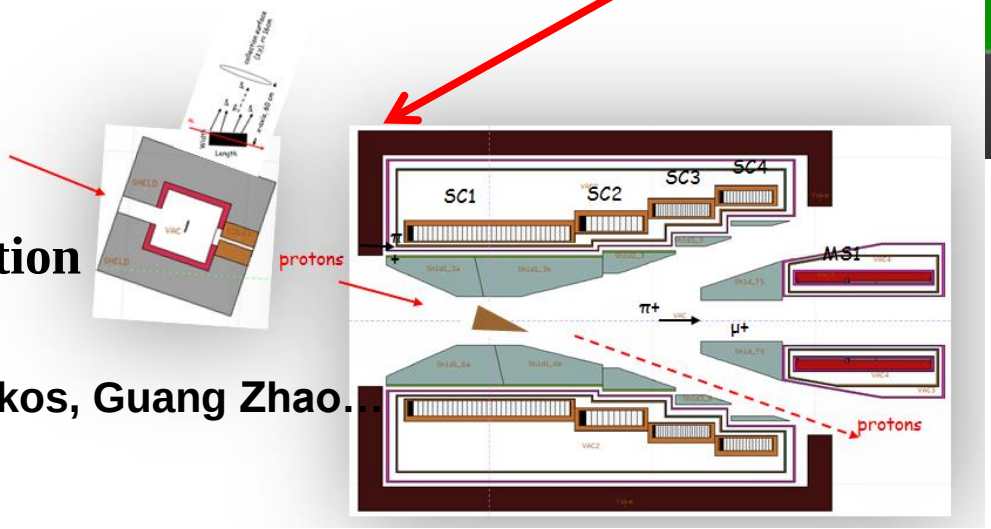
Courtesy: Jiang-Yu Tang

Overview of EMuS

- Build the first accelerator muon source in China?





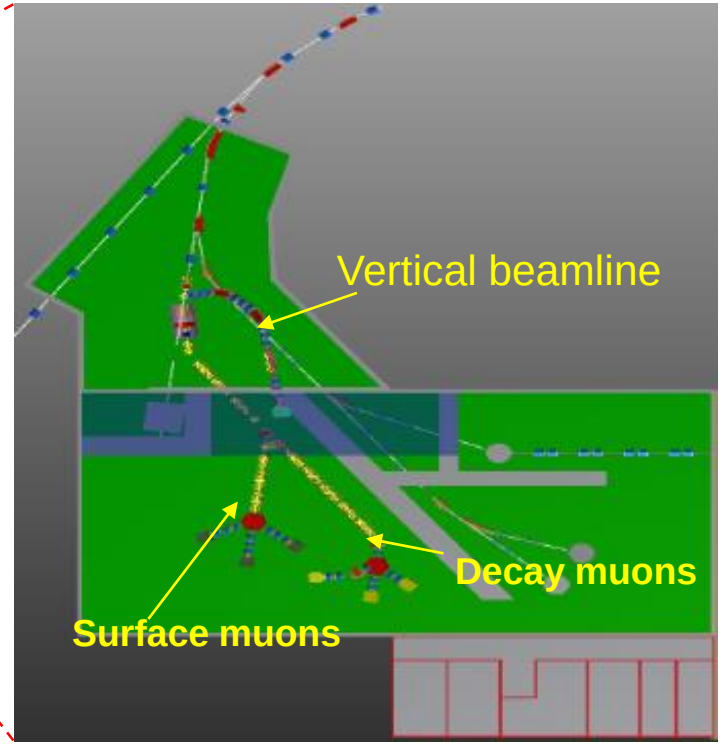


Target station

Courtesy:
Ye Yuan, Nikos, Guang Zhao…

Courtesy: Jing-Yu Tang, Yu Bao

Overview of EMuS



- Conceptual design of EMuS is almost done. Part of proposal in CSNS-II upgrade plan.
- Superconductor solenoid might help to reach intensity 10^9/s: ~100 of PSI in 1999.

Muonium conversion can be also conducted with an even higher muon intensity at ADS&HIAF in the close-by accelerator center.

Ref: slides@EMuS workshop2019

EMuS in a comparison with international muon sources

	Proton driver [MW]	Surface muons			Decay muons		
		Intensity [1E6/s]	Polarization [%]	Spread [%]	energy [MeV/c]	Intensity [1E6/s]	Spread [%]
PSI	1.3	420	90	10	85-125	240	3
ISIS	0.16	1.5	95	<15	20-120	0.4	10
RIKEN/RAL	0.16	0.8	95	<15	65-120	1	10
JPARC	1	100	95	15	33-250	10	15
TRIUMF	0.075	1.4	90	7	20-100	0.0014	10
EMuS	0.005	83	50	10	50-450	16	10
Baby EMuS	0.005	1.2	95	10			

×5 CSNS-II upgrade

- Better extraction efficiency with SC solenoid.
- Better muon sources with higher energy.
- Plan to optimize the beamline for better polarization and higher intensity

Ref: JY Tang slides @2019EMuS&MOMENT workshop in SYSU

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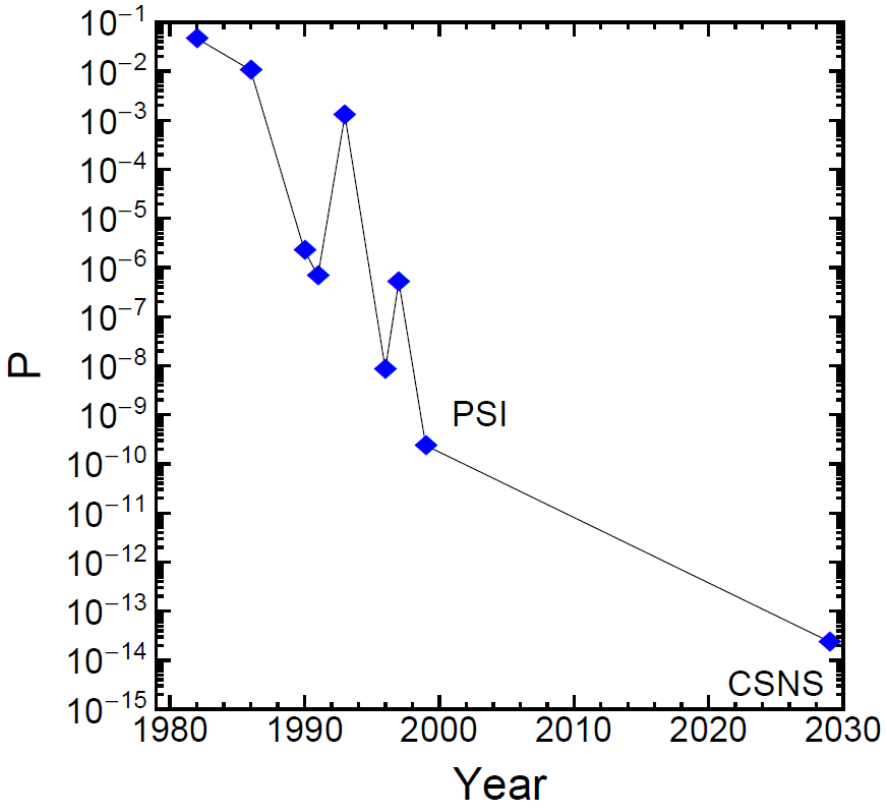
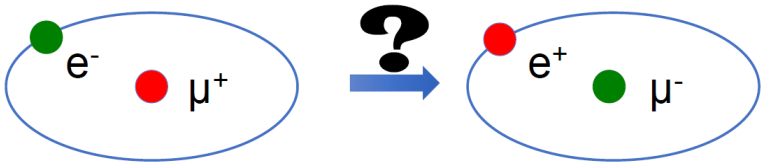
Fundamental science with EMuS





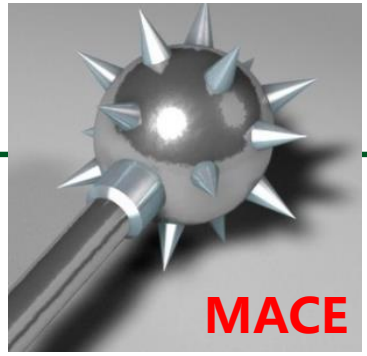
- The latest bound was done at PSI more than 20 years ago with a muon intensity $8 \times 10^6 \mu^+/s$ and high-precision magnetic spectrometer.
- Timing resolution in detector: ~ ns
- Position resolution in detector: ~ mm
- EMuS plan to offer $10^9 \mu^+/s$
- Current timing resolution in detector: ~ ps
- Current position resolution in detector:~μs
- Expect to be improved by > O(10^2)?

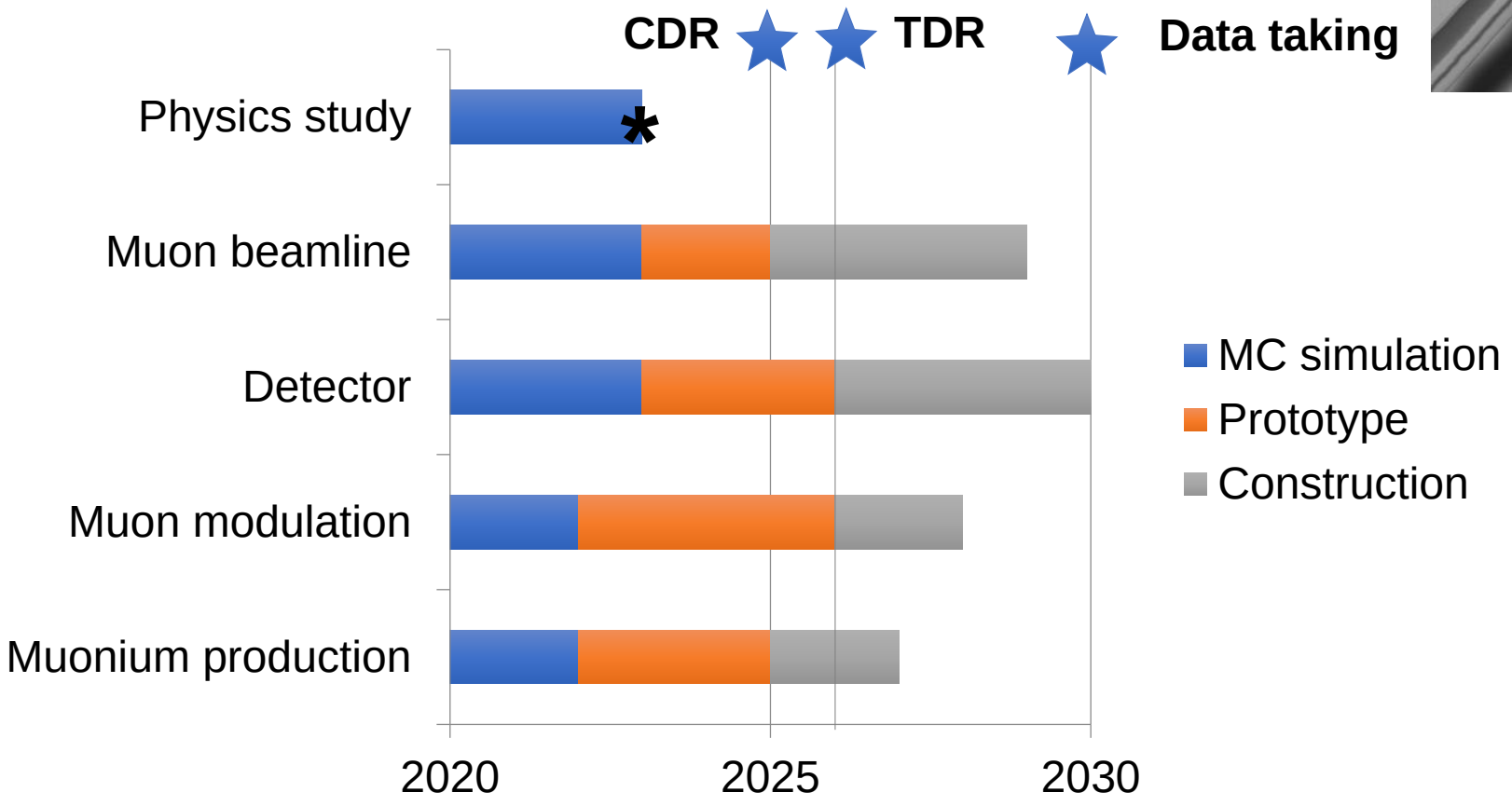
- No progress since 1999.
- **Step further with better timing/tracking capability in a magnetic spectrometer?**

Recent progress in the R&D

- Preliminary study:
  - CDR of EMuS at CSNS was reviewed by international experts in November, 2018.
  - R&D of muonium productions was first tested at PSI.
  - Simulation tool for muon beamlines is almost finished.
  - Cooperation with PSI, ISIS in RAL, RIKEN and Osaka U.
- Platform support:
  - CSNS-II will provide the high-intensity proton driver.
- Team support:
  - IHEP has a team of experts in R&D of the accelerator and detector.
  - Accelerator physicists: Jing-Yu Tang, Han-Tao Jing, Yu Bao…
  - Detector and physics: Rui-Rui Fan, Hai-Bo Li, Ye Yuan, Yao Zhang…
  - Sun Yat-Sen University team: Yu Chen(electronics), Yu-Zhe Mao (MC by G4), Jian Tang(physics and detector).
  - Welcome all to joining the project to achieve the best sensitivity in the world.
- Funding support:
  - CAS fundamental science program for IHEP: muon beam design and optimization
  - NSFC funding for SYSU to support physics performance study & detector specifications.
  - R&D of the new magnetic spectrometer is missing…

Roadmap and milestones

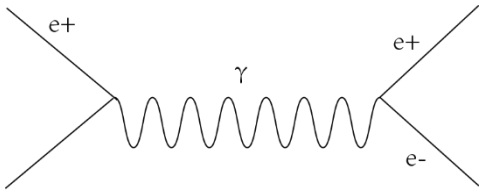


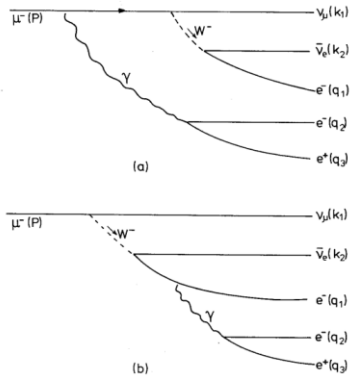


*Expect to get support from the local province.

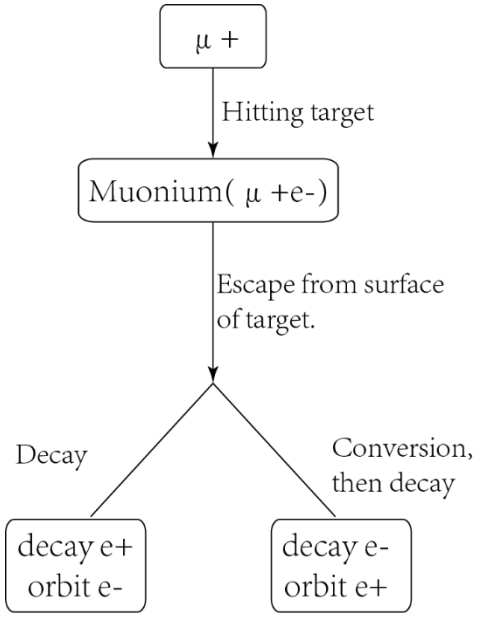
Preliminary MC simulation

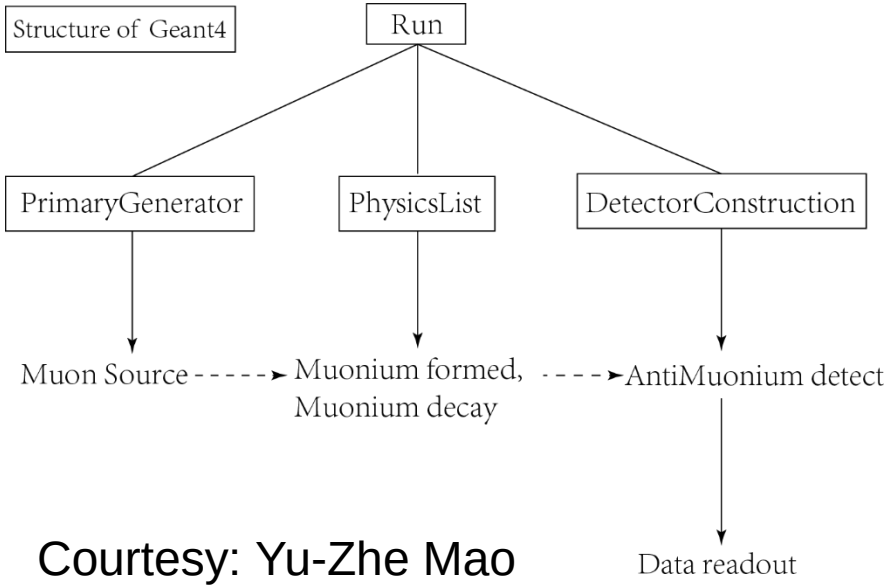
- Backgrounds:
  - μ^+ decays to e^+, Bhabha scattering to generate high-energy e^- in coincident with low-energy e^+
  - μ^+ decays: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu} e^+ e^-$





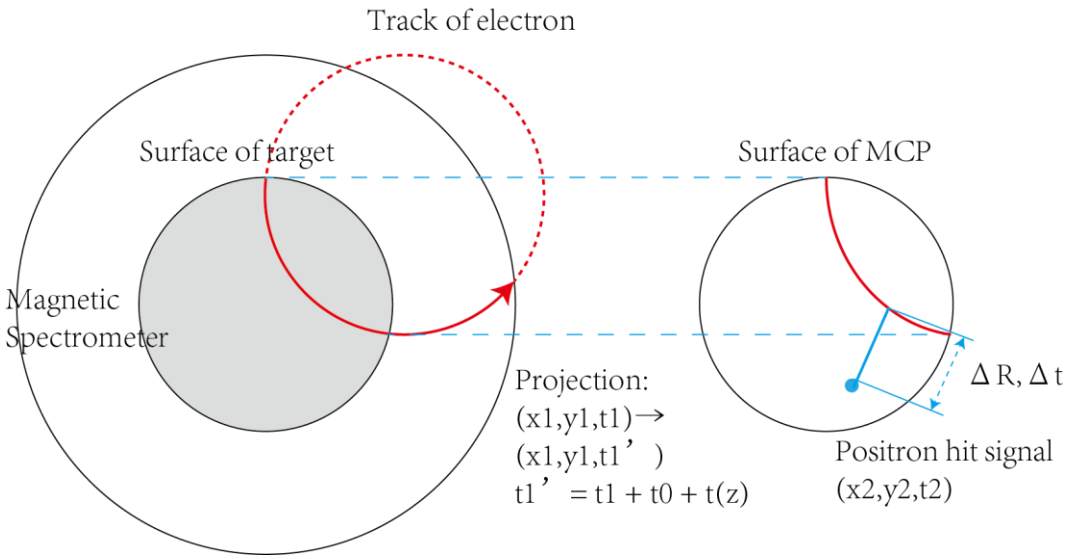
- Antimuonium decay signal by position-time coincidence
  - High energy Michael electron ~ O(10) MeV -- TPC
  - Low energy orbital positron ~ O(10) eV -- BGO

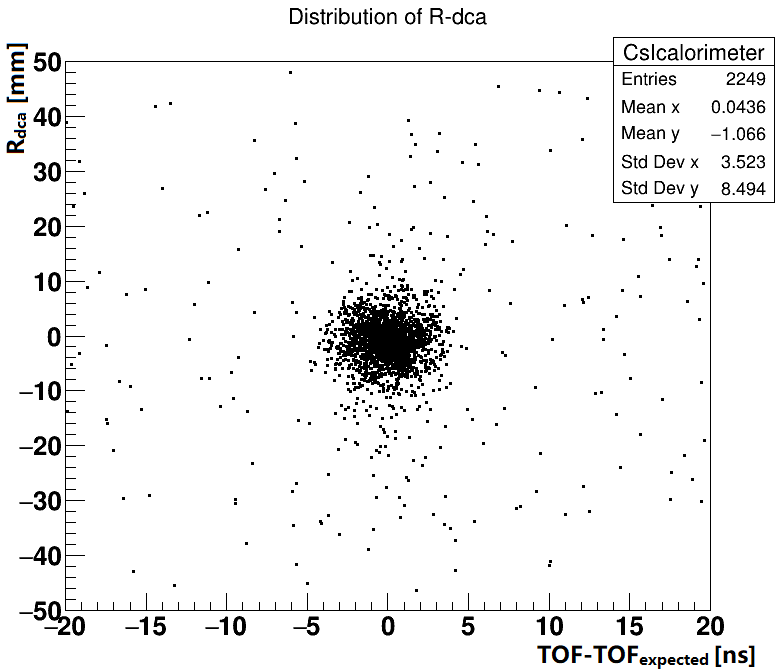




Courtesy: Yu-Zhe Mao

Muonium generators in MC simulation





- Injected muons: 1.2×10^5 of μ^+
- In our simulation, 76% detection efficiency.
- Consistent with PSI muonium formation results.

- Happen at the same vertex:

  $|\Delta R| \sim R_{dca} < 12.0$ mm
- Happen at the same time:

  $|\Delta t| \sim TOF\text{-}TOF_{expected} < 4.5$ ns:
  TOF = t0 + t(z)

Courtesy: Yu-Zhe Mao

Rare decays in MC simulation

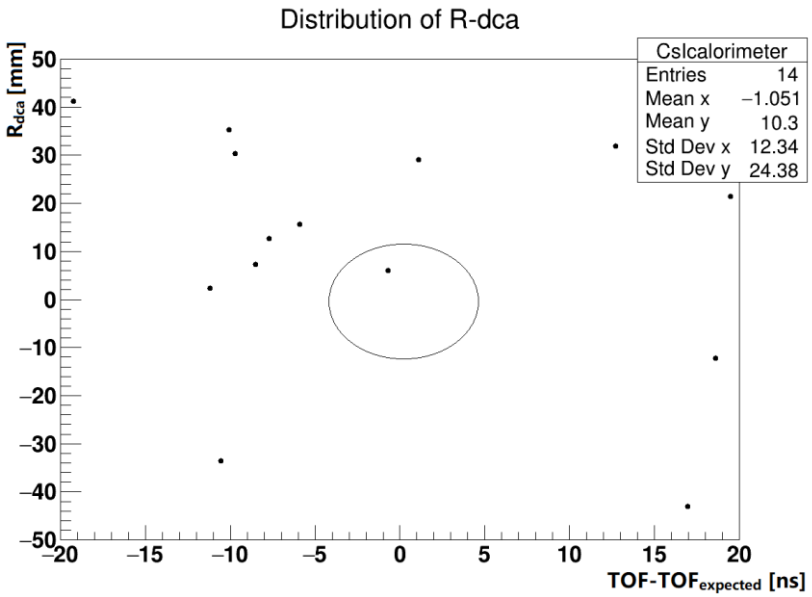
Preliminary results in simulation

- 1.056×10^8 of μ^+
- BR of $\mu^+ \to e^+e^-e^+\nu_e\overline{\nu_\mu}$

is set to 100%.

Compared with PSI estimates

- 9.459×10^7 of μ^+ Rare decay
- 1.7 background events expected.



- Happen at the same vertex:

  $|\Delta R| \sim R_{dca} < 12.0$ mm
- Happen at the same time:

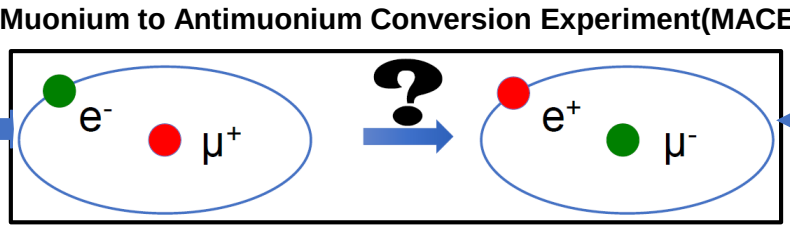
  $|\Delta t| \sim \text{TOF-TOF}_{expected} < 4.5$ ns:

  TOF = t0 + t(z)

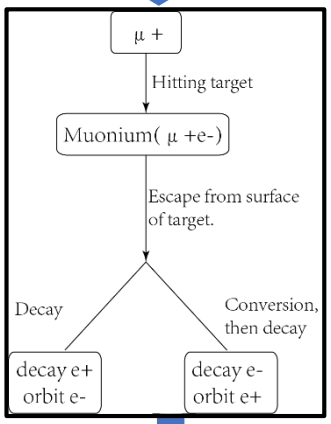
Courtesy: Yu-Zhe Mao

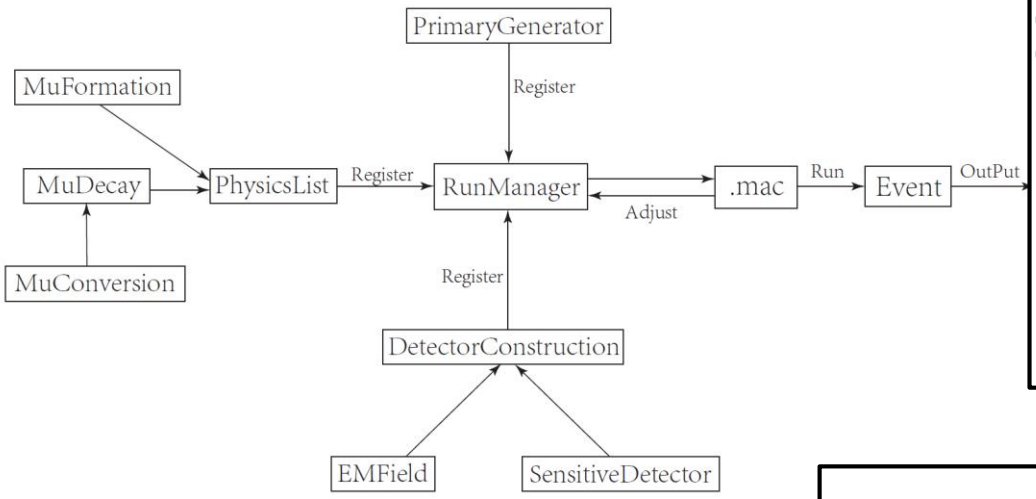
MC simulation to support MACE

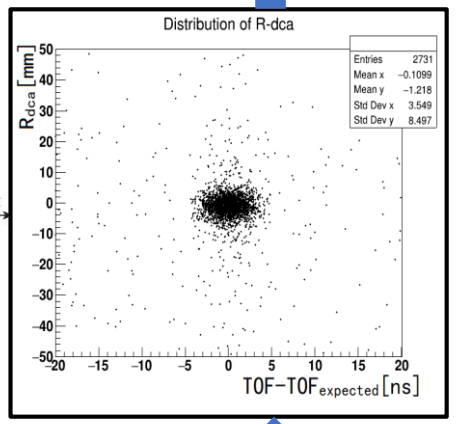
New target with better efficiency?



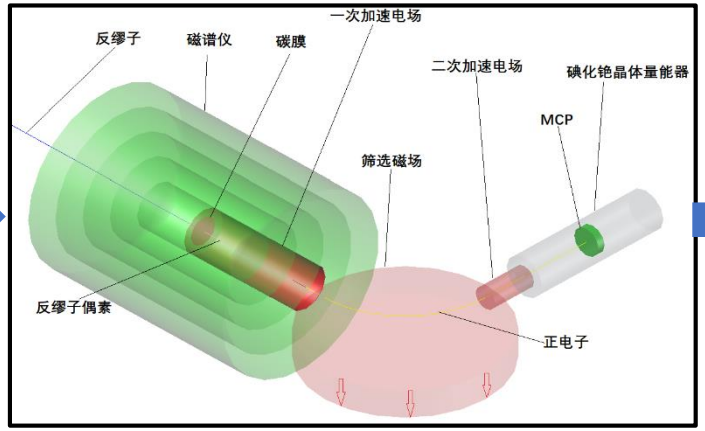
New ROI for better S/B?

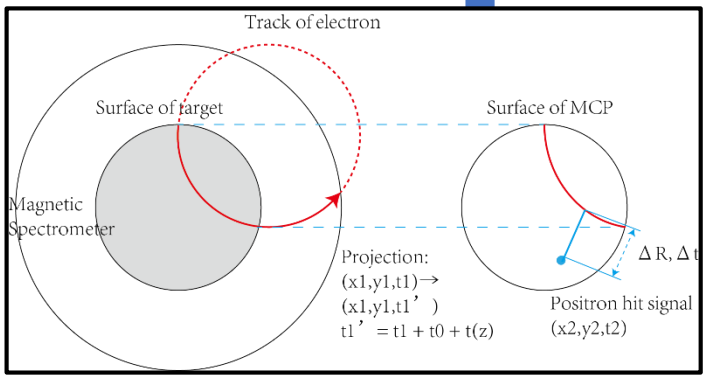






New design with better resolutions?

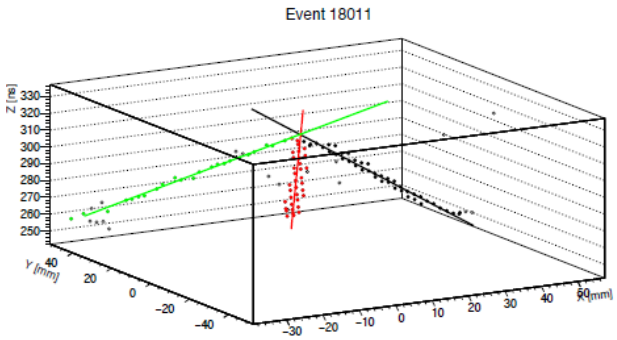




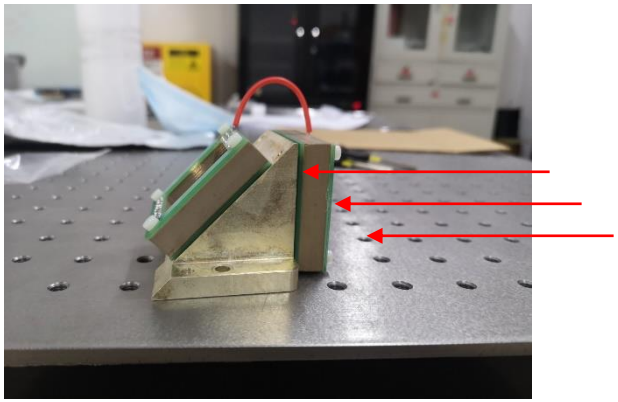
New ideas…

Detector R&D

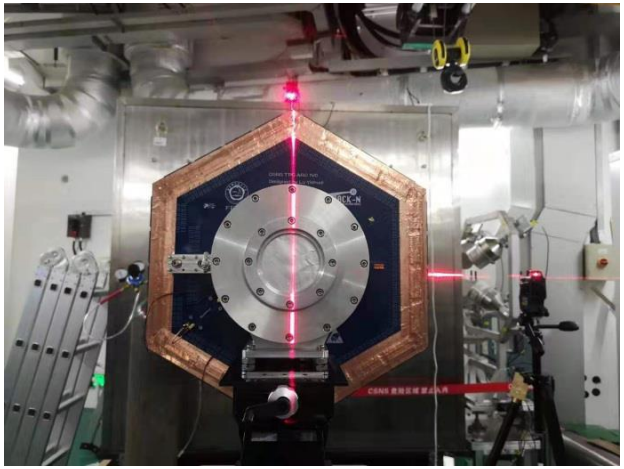
- Overlap with other projects developed by CSNS team.



Positron detector by CsI



Electrostatic mirror



TPC prototype

Courtesy: Rui-Rui Fan

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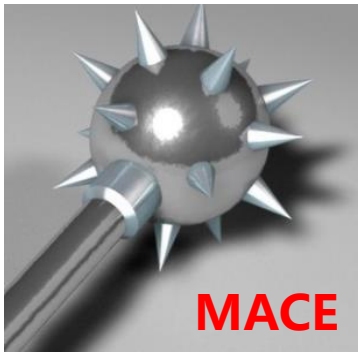
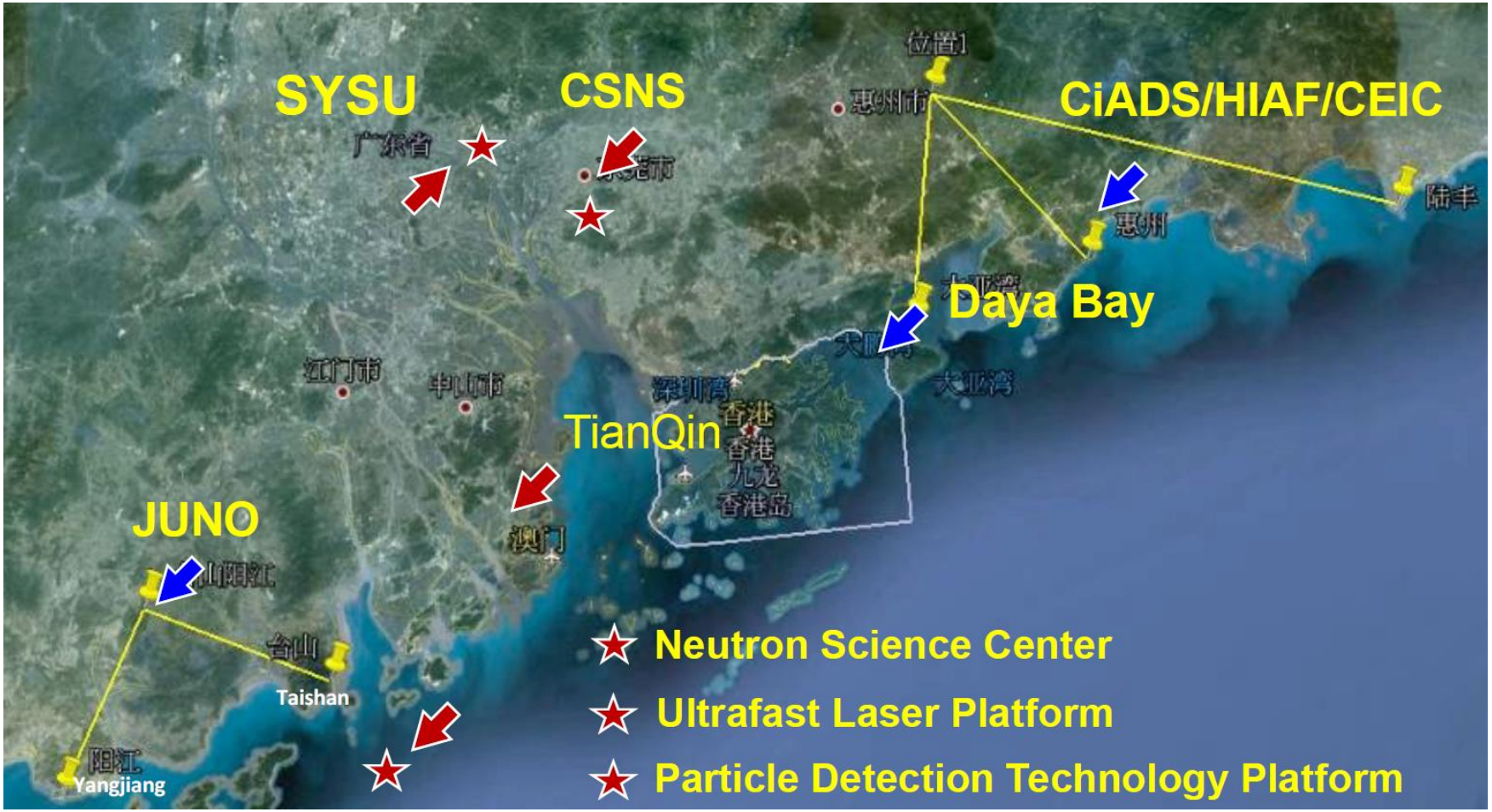
Summary

- Hot topics to do precision measurements of QED and search for new physics with accelerator muon sources.
- We naively proposed an experiment to search for muonium to antimuonium conversions: aim at **the best sensitivity** in the world, a potential **breakthrough** in the intensity frontier.
- MACE will boost the innovative design in muon beamlines, muonium productions, high time and spatial resolution detectors. **Aim at two orders of magnitude** better than the latest limit.
- Welcome all to pushing forward the Muonium to Antimuonium Conversion Experiment.

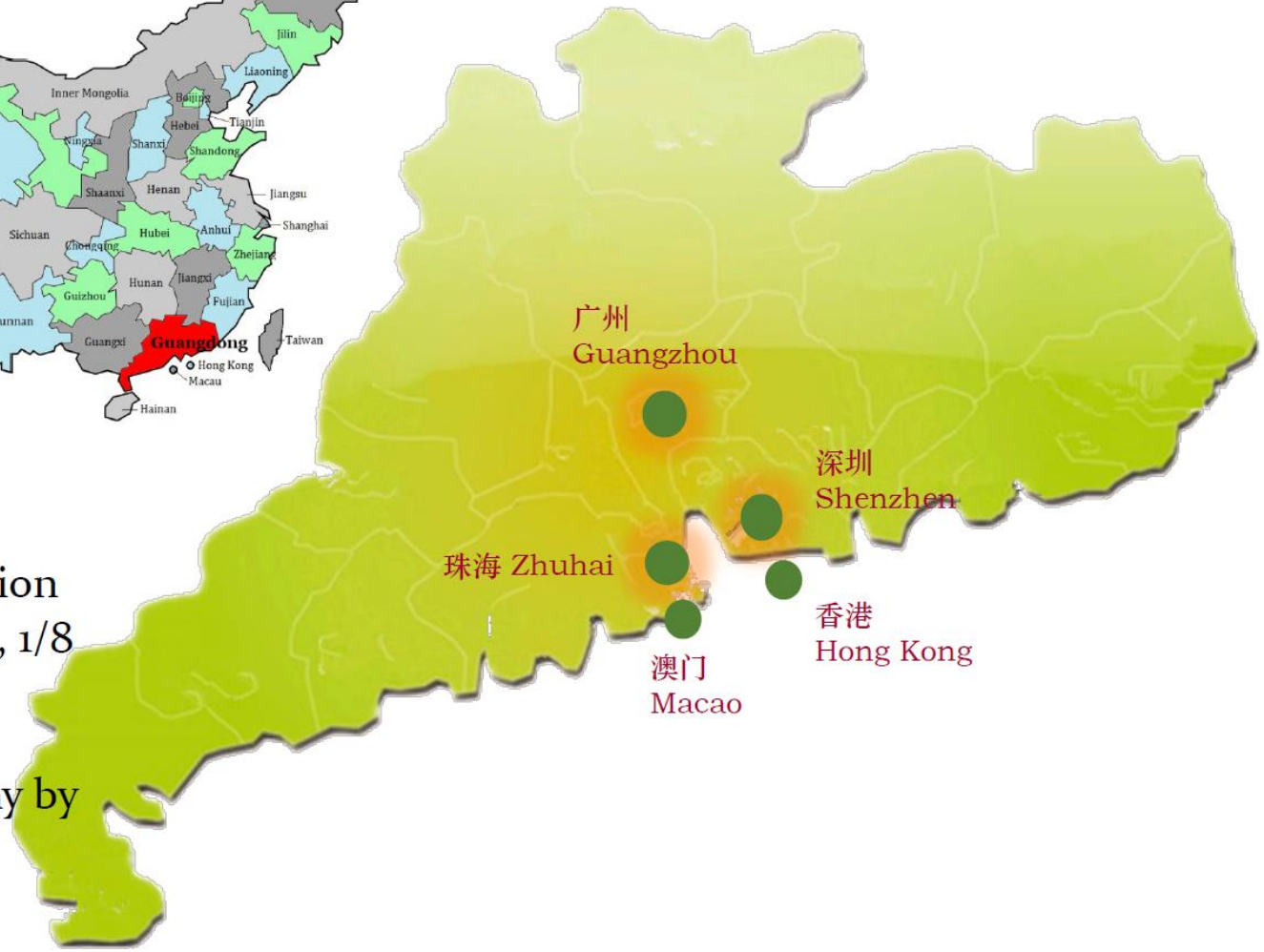


PostDoc advertisement in SYSU



- Postdoc openings in our group for muon physics: **~2K euros/month after tax + bonus + on-campus housing + Postdoc funding** supported by local province**.**
- Please contact me by email: tangjian5@mail.sysu.edu.cn

Guangdong-Hong Kong-Macao Greater Bay Area



- Population: ~100M
- GDP: RMB 11.7 trillion ($1.83 trillion) in 2017, 1/8 of national total
- Largest bay economy by 2020

THANK YOU